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IMPLEMENTATION OF VARIABLE FREQUENCY DRIVE (VFD) FOR SHIPBOARD APPLICATION

U. RAMA KALYANI[1] & B. NAGESWARA RAO[2]

[1]M Tech Student, Department of Electrical & Electronics Engineering, CVSR College of Engineering, Hyderabad, Andhra Pradesh, India

[2]Assistant Professor, Department of Electrical & Electronics Engineering, CVSR College of Engineering, Hyderabad, Andhra Pradesh, India

ABSTRACT

A variable-frequency drive (VFD) (also termed adjustable-frequency drive, variable-speed drive, AC drive, micro drive or inverter drive) is a type of adjustable-speed drive used in electromechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. BLDC motor is used in many wide range applications. In Brush less DC motor several cases are used in those techniques they are inverter and PWM inverter technique. The brushless dc motor used the variable frequency drive for shipboards application. This paper describes a simpler way to control the speed of PMBLDC motor using pwm control method. It is suitable for both sensor and sensor less methods of PM BLDC motor control. Although using the sensor less mode has big advantages in terms of cost and size, it makes the motor drive a little more complicated. These all above conditions are verified by simulation by using MATLAB/Simulink software.

KEYWORDS: PMBLDC, PWM Inverter, VFD

INTRODUCTION

Large scale deployment of VFDs for shipboard systems, with their accompanying benefits, has not yet been realized because they are competing with the size/weight allocations of typical motor controller which are considerably smaller than state of the art VFD solutions. Therefore more innovative, power dense solutions are required that will ultimately enable the VFD to claim the same real estate as the motor controller.

Brushless DC electric motor (BLDC motors, BL motors) also known as electronically commutated motors (ECMs, EC motors) are synchronous that are powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive the motor. In this context, AC, alternating current, does not imply a sinusoidal waveform, but rather a bi-directional current with no restriction on waveform. Additional sensors and electronics control the inverter output amplitude and waveform and frequency, while the BLDC VSI enables the functional realization between a DC source and the PM motor, the overall solution also requires an AC to DC converter in the power flow chain. In this context, a PWM CSR interface to the 3 phase 440VAC input has already been developed for shipboard use

The AC electric motor used in a VFD system is usually a three-phase induction motor. Some types of single-phase motors can be used, but three-phase motors are usually preferred. Various types of synchronous motors offer advantages in some situations. The VFD controller is a solid state power electronics conversion system consisting of three

distinct sub-systems: a rectifier bridge converter, a direct current (DC) link, and an inverter. Voltage-source inverter (VSI) drives (see 'Generic topologies' sub-section below) are by far the most common type of drives.

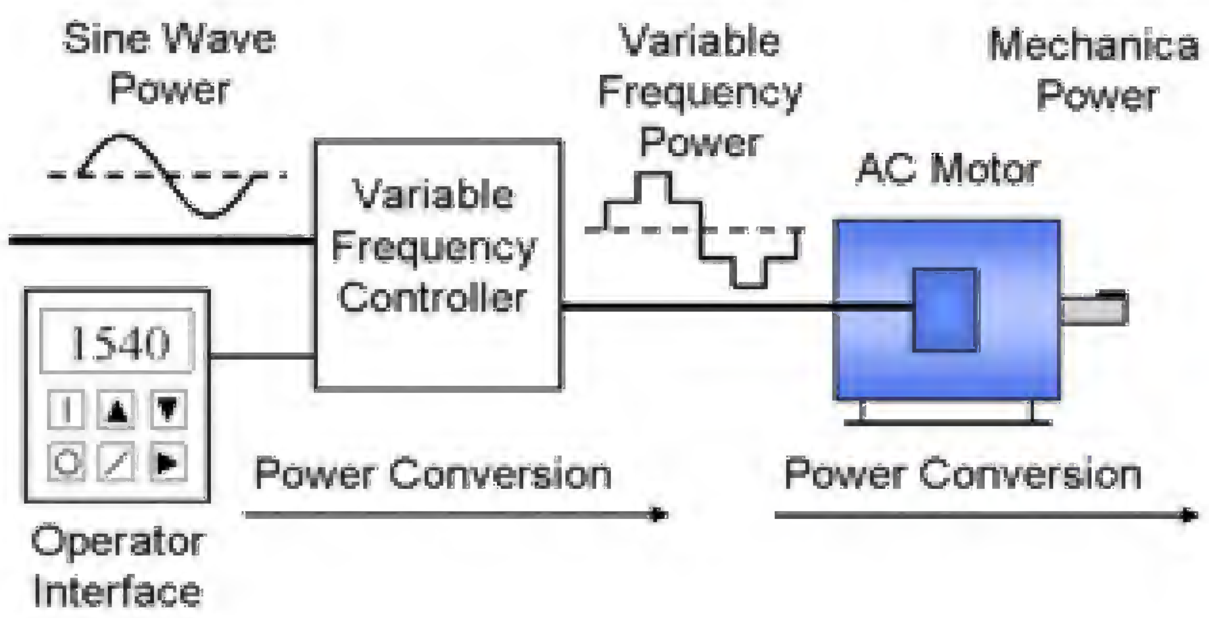

Figure 1(a): VFD System

VFDs are used in applications ranging from small appliances to the largest of mine mill drives and compressors. However, about a third of the world's electrical energy is consumed by electric motors in fixed-speed centrifugal pump, fan and compressor applications and VFDs' global market penetration for all applications is still relatively small. This highlights especially significant energy efficiency improvement opportunities for retrofitted and new VFD installations.

PRESENTLY AVAILABLE VFD SOLUTIONS

The Commercial Off-the-Shelf (COTS) VFD shown in Figure 2 has become the economically viable choice for industry applications because it appears to achieve both functions required for AC to AC power conversion chain—AC to DC and DC to AC conversion—with the least amount of additional parts.

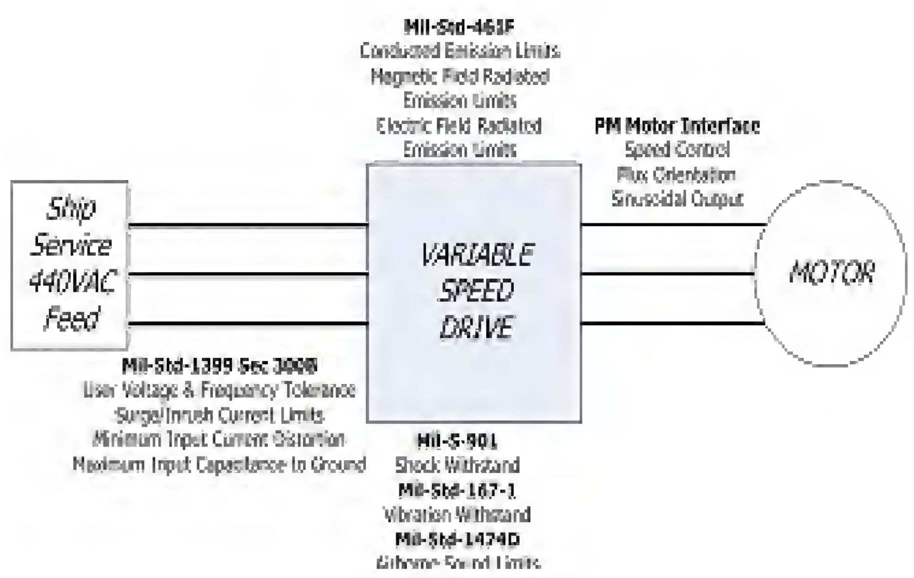

Figure 1(b): VFD Interface Requirements

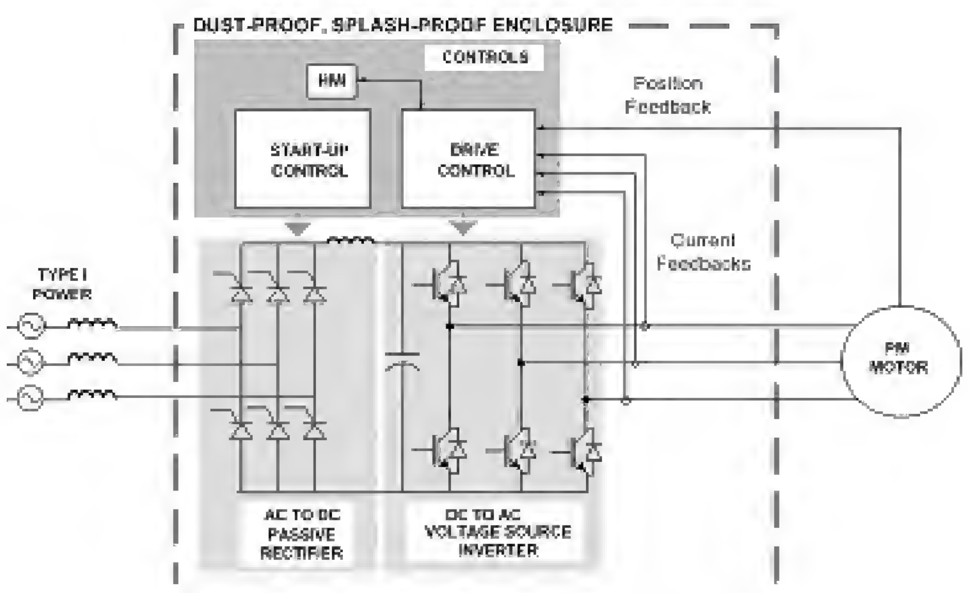

Figure 2: COTS VFD Solution

However, while the basic functionality required for controlling a PM motor may be achieved with this solution it is incompatible with the shipboard environment for the following reasons:

- Low order harmonic currents resulting from diode rectification exceed the maximum Individual Harmonic Distortion (IHD) limit of 3% [4]
- High frequency common mode voltage on the source side, high rates of change of voltage with time (high dV/dt) and high reverse recovery currents that reflect into a Line Stabilization Network (LISN) for test compatibility purposes [5] are un-attenuated
- High frequency common mode voltage on the load side result in common mode currents that flow into motor bearings and reduce their lifetime
- High output current rates of change of current with time (high di/dt) increase motor losses and torque ripple A modified COTS VFD can replace the passive rectifier with a Voltage Source Rectifier (VSR) to control low order current harmonics (implemented with the same hardware as the VSI), add associated filter and control hardware and "cocoon" all components in a shock-proof, EMI-tight enclosure. The "cocooned" COTS VFD is shown in Figure 3. The downside of this approach is that additional filter and control hardware contribute significantly to overall size and weight. The COTS VFD itself represents less than 6% of the total volume and weight [6]. Some increase in power density can be achieved by custom, mil-hardened designs but at significant cost. Size envelopes have been developed for shipboard VFDs based on these considerations as a function of horsepower [3]. For example the maximum required envelope for a 10Hp (7.5kW) VFD is 24" x 12" x 35" based on what is practically achievable with commercially available VSI solutions. High penetration of VFDs on a ship is severely limited by this space claim. Therefore, further work is required to understand the drivers behind power density and to come up with novel approaches that eliminate additional parts and improve upon power density.

TOPOLOGY CONSIDERATIONS

Figure 5 shows the VSR/VSI topology of Figure 3 as a network of multiple throw switches and a capacitor energy storage device connected between a three-phase current source and sink. If the inductances of the electrical grid and motor are sufficiently high and the effects of common mode voltage an inrush current are neglected then it would seem that the voltage source converter VFD implementation has a minimum number of parts. However, Figure 3 indicates this is not the case. The VSR/VSI cannot be compatible with the shipboard system without the additional hardware represented in Figure 3 as explained below. First, the real world implementation of switch Sa, Sb or Sc of Figure 5 is shown in Figure 6. The positive current (from source to sink) that flows through force commutated Insulated Gate Bipolar Transistors (IGBTs) that can be turned off and on at will. However, the negative current that flows through diodes is commutated by the DC link voltage. So, when the source voltage is applied with a fully discharge DC link capacitor (vb=0) the VFD presents a short circuit to the system. Second, when considering the sufficiency of the inductance of the electrical grid in present a current sink to the VSR in the practical system the source inductance should contribute less than 3% voltage droop in order to keep user voltage tolerance to within the required ±5% [4].

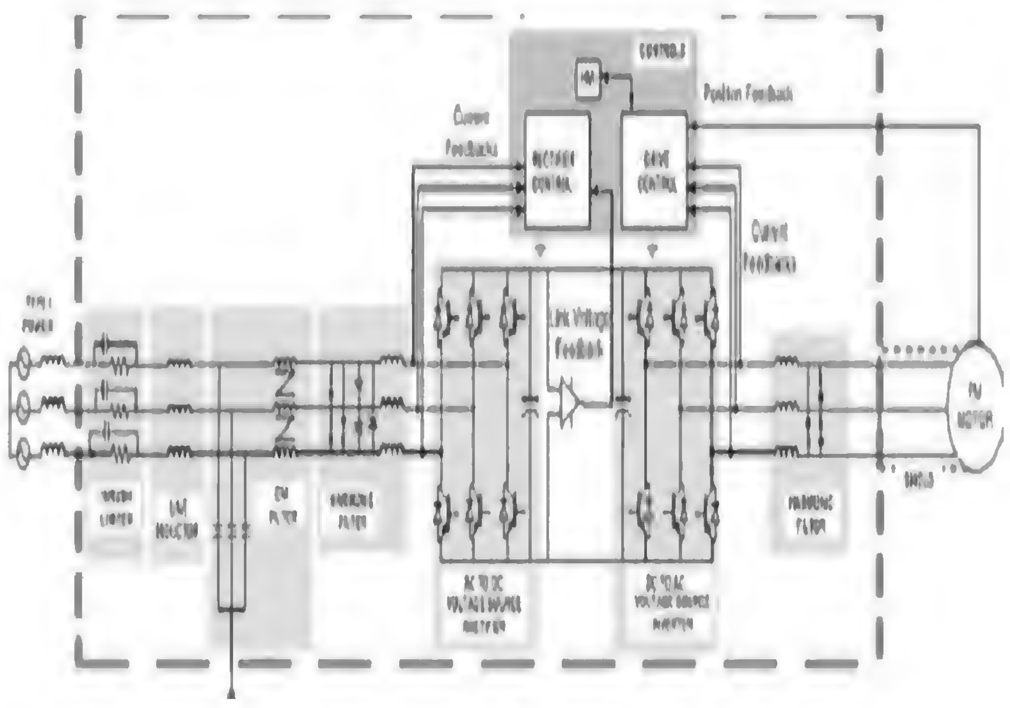

Figure 3: Shipboard Compatible VSR/VSI

In order for the source impedance to be sufficiently high on the source (VSR) side the source inductance contribution should be closer to 10% and inductance will be necessary on the load side if a PM motor is used.

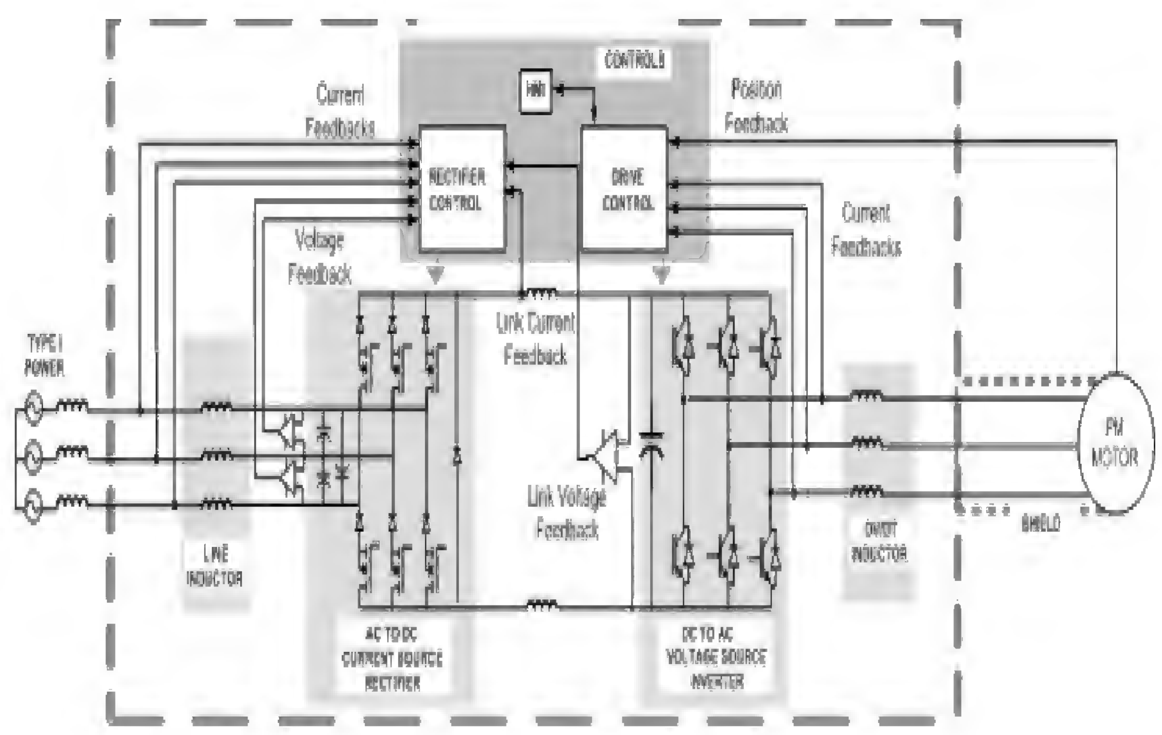

Figure 4: Shipboard Compatible CSR/VSI

Third, the VSR/VSI topology inherently drives non-zero common mode voltages that drive common mode currents into the system—the source of conducted EMI emissions on the input and bearing currents on the output. This is understood by considering the relationship between the switching functions, habc and huvw for the throws of switches Sabc and Suvwin Figure 5 and line to ground voltages on each phase where

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{v_b}{2} \cdot \begin{bmatrix} h_a \\ h_b \\ h_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \frac{v_b}{2} \cdot \begin{bmatrix} h_u \\ h_v \\ h_w \end{bmatrix} \tag{2}$$

The VSR/VSI is constrained so that ha+hb+hc≠0 and hu+hv+hw≠0. Therefore, the common mode circuit shown in Figure 7 demonstrates that the common mode current, and hence the emissions, can never be driven to zero. The result is that a front end EMI filter that includes capacitance to ground to shunt common mode current to ground at the VFD itself is always necessary. Finally, (1) and (2) demonstrate that pulsed voltages are applied to the source and sink sides of the VSR/VSI. On the source side high frequency voltage content gets reflected onto the LISN, so EMI testing will deem the system incompatible unless differential mode capacitors with very low leakage inductance are added across the lines. This differential mode capacitance cause ringing with the source unless a damping circuit is added and the source impedance is defined by adding additional inductance to swamp out unpredictability of the source impedance. Also, high dv/dt applied to the motor will affect its insulation rating and contribute to losses unless sufficient inductance is added to

the VSI output. The VSR/VSI can only be made shipboard compatible by driving up the size and weight of the system with the following additional components/sub-systems:

- Add inrush limiting circuitry
- Add inductors is series with the VSR inputs
- Add a EMI common mode inductor and line capacitors to ground for each phase
- Add differential mode capacitors across the source side of the added inductors
- Add a damping circuit and sufficient line inductance to swamp out the impedance of the ship service feed
- Add inductors in series with the VSI outputs
- Add to the cooling system as necessary to deal with heat from the additional components

An alternate topology for the VFD is to replace the VSR with a CSR as shown in Figure 8. The CSR is a network of multiple throw switches and between three-phase voltages Source and inductive energy storage device. While this topology has more components than the VSR/VSI it starts out as being fundamentally compatible with the shipboard system as explained below. First, the real world implementation of switch Sip or Sin of Figure 8 is shown in Figure 9. Here, positive flowing current is flowing through a Mos-Controlled Field Effect Transistor (MOSFET) in series with a diode. When the MOSFET is gated off positive flowing current is blocked. Second, since the purpose of the input capacitors is to present a relatively stiff voltage source to the CSR the voltage across them will present a sinusoidal voltage to the electrical grid if the CSR is controlled correctly. Third, the CSR topology inherently drives no common mode current into the system. This is understood by considering the relationship between the switching functions, habc for the throws of switches Sip and Sin in Figure 8 and line currents of each phase.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} h_{ap} & h_{an} \\ h_{bp} & h_{bn} \\ h_{cp} & h_{cn} \end{bmatrix} \cdot \begin{bmatrix} i_p & i_n \end{bmatrix} \quad (3)$$

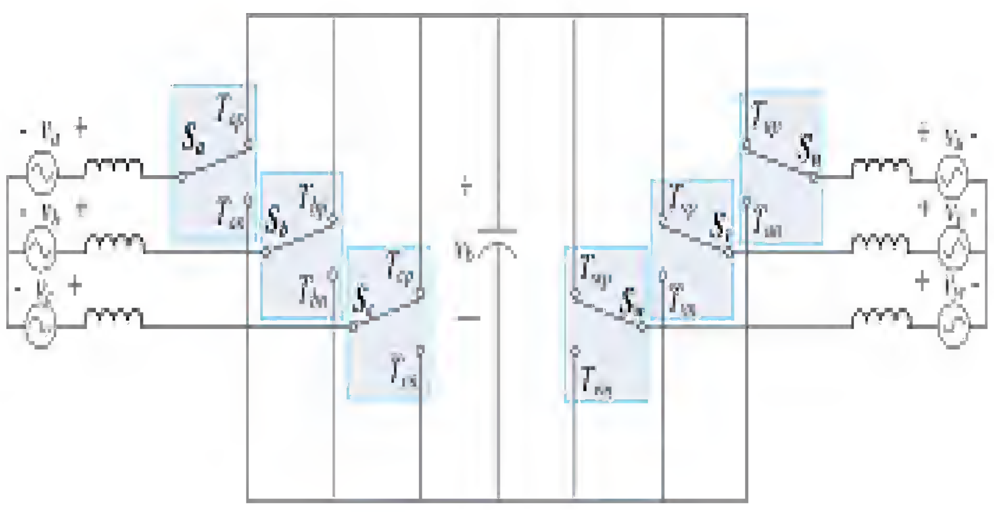

Figure 5: VSR/VSI Topology

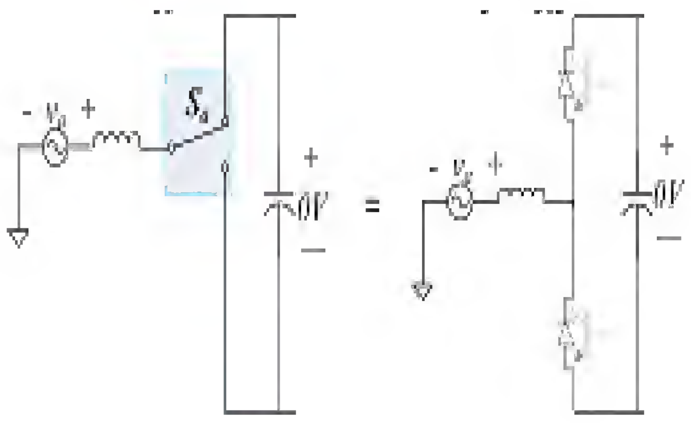

Figure 6: VSR Pole at Start-Up

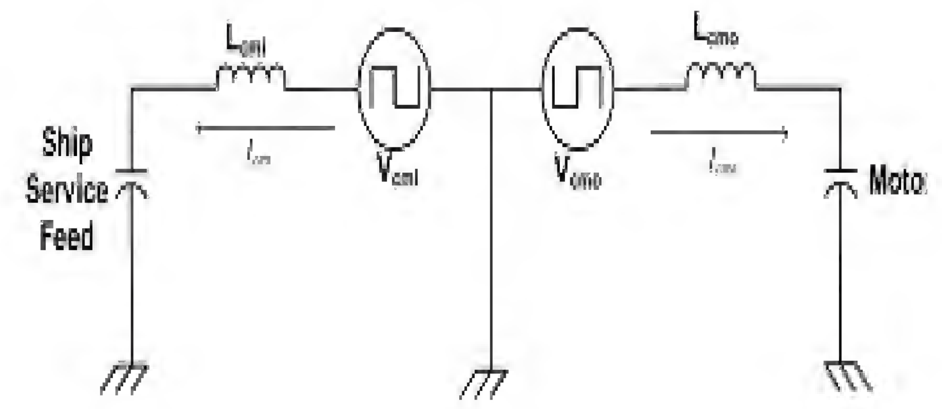

Figure 7: VSR/VSI Common Mode Circuit

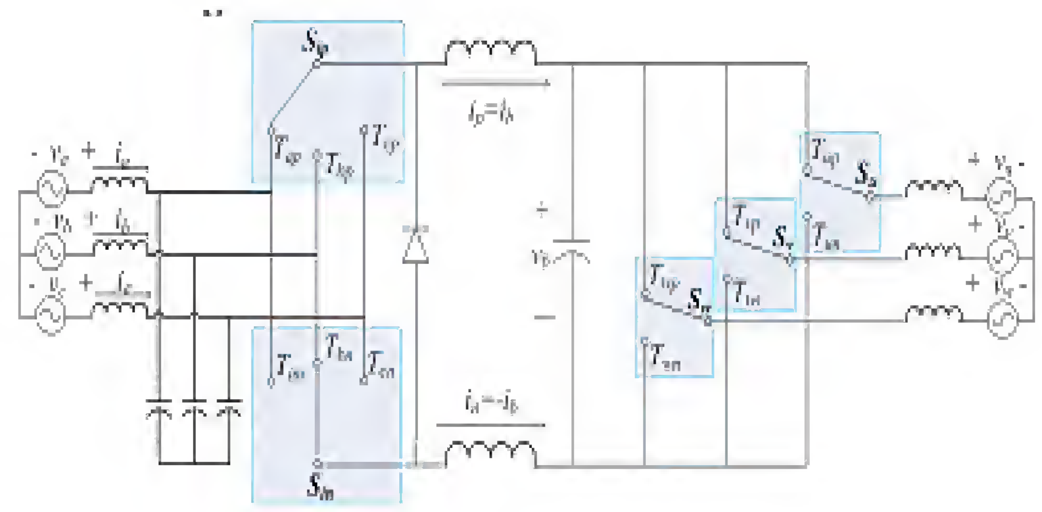

Figure 8: CSR/VSI Topology

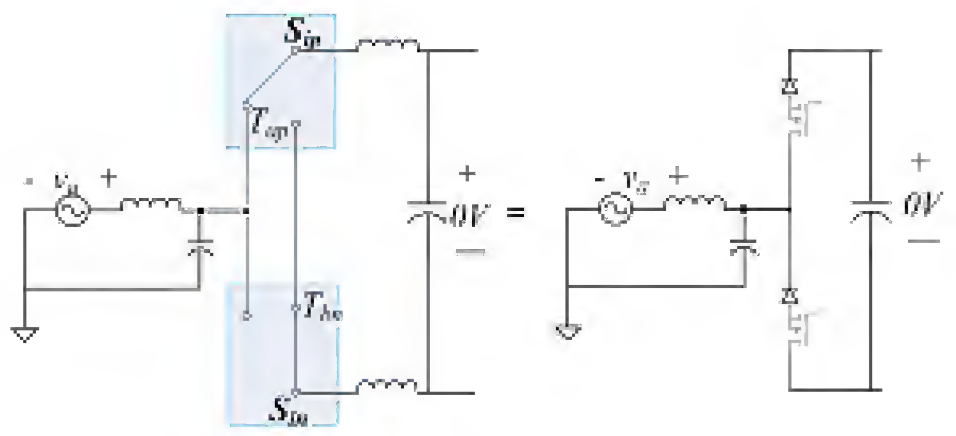

Figure 9: CSR Pole at Start-Up

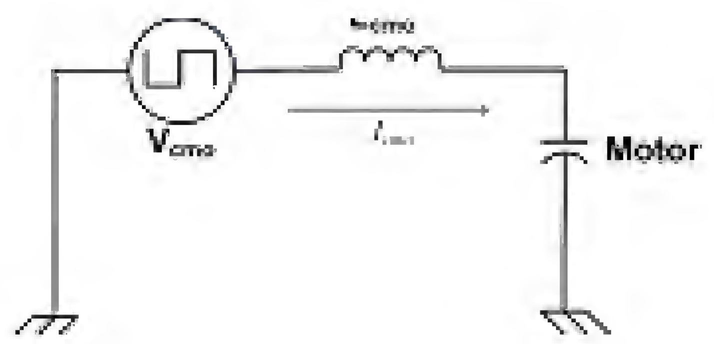

Figure 10: CSR/VSI Common Mode Circuit

Because the CSR is constrained so that hap+hbp+hcp=1and han+hbn+hcn=1, and there is a freewheeling diode to ensured continuous conduction of the current, ib, through the inductor such that ip= ib=-in, the common mode current, ia+ib+ic=0— even during switch transitions. Therefore, no components associated with common mode EMI filtering are required. Although the CSR does not impress pulsed voltages on the source, it may be necessary to add passive damping circuitry to deal with any resonances between the CSR and the upstream source or through appropriate active damping using controls. A shipboard compatible VFD based on the CSR/VSI topology is shown in Figure 4. Comparing this topology with Figure 3, it is clear that fewer components are required. Since the input filter and EMI filter are the largest components, it is expected that this system will be more power dense. In previous work there has been some comparisons made between the CSR and other topologies but not in the context presented here [7], [8]. A drawback to this approach is that the both the CSR and VSI are buck converters. With a 440VAC input, the maximum DC voltage that can be achieved is 500V. Therefore, the application of the topology in Figure 4 is limited to systems where the required motor voltage is 350VAC or lower. The CSR/VSI topology is a considerable improvement when compared to the VSR/VSI topology; the voltage limitation poses a serious drawback as a general purpose VFD solution for shipboard systems. In order to apply the VFD across a range of applications, a CSR feeding a Current Source Inverter (CSR/CSI) topology would represent the logical next step in the topological evolution. This approach has recently received considerable attention in the literature as an alternative to VSR/VSI that is significantly more power dense and has some distinct advantages for low horsepower

(<20Hp) applications because the topology lends itself well to the use of SiC MOSFETs which can achieve much higher switching frequencies than IGBT-based converters [9], [10].

CONTROL ARCHITECTURE

CSR Controls

The CSR controls consist of three main components: the outer DC voltage loop, inner cascaded DC Buck current loop, and a modified space vector modulator. The outer DC Link voltage regulator uses a Proportional-Integral-Derivative (PID) loop to generate the DC link current set point. The inner CSR DC link current regulator uses a PID loop to generate the CSR duty cycle command which is further processed with a bound function to generate the actual switching duty cycle for the space vector modulator. The bounding function of the duty cycle command is intentionally limited to the non over modulation range of the PWM module. Over modulation is not employed in the CSR controls due to the non-linearity it introduces on the phase currents which would violate the ship interface maximum current THD requirement of 3% [4].

The CSR space vector modulator uses the duty cycle command from the DC link current loop and a synthesized electrical angle reference to generate the actual power device switching gate functions. The CSR modulator defines six distinct 60° sectors in the 360° electrical angle reference frame shown in Figure 11. In each sector there are three actively switching gates: one primary device which is fully on and two secondary devices which alternate switching in an interleaved pattern. Figure 12 shows which power devices are active in a given sector. The switching functions of the secondary devices are sinusoidal to generate input currents that match the phase and magnitude of the input line voltages. For example, in Sector 1 of Figure 12 the A Upper switch is the primary device which is fully on during the entire sector and the C Lower and B Lower switches are the secondary devices which are actively switching. For sector 1 the switching functions are as follows [11]:

$$T_{AUpper} = 1 \tag{4}$$

$$T_{BLower} = \frac{m \cdot \sin(\alpha)}{\sin(60^o)} \tag{5}$$

$$T_{CLower} = \frac{m \cdot \sin(60^o - \alpha)}{\sin(60^o)} \tag{6}$$

Where α is the sector angle between 0°and 59° and m is the duty cycle modulation index defined as the ratio between the peak input voltage and desired output voltage. The current in the phase A upper switch, which remains on for the entire sector, is equal and opposite to the sum of the current in phase B lower and phase C lower, which are actively switching. In effect the modulation of the phase B and phase C currents inherently controls the current in phase A so in each sector all three phase currents are control by only two active switching devices.

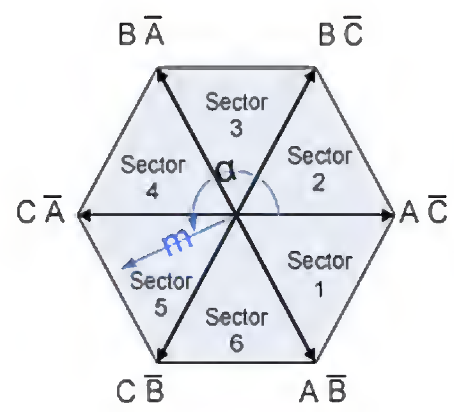

Figure 11: Definition of CSR Modulator Sectors

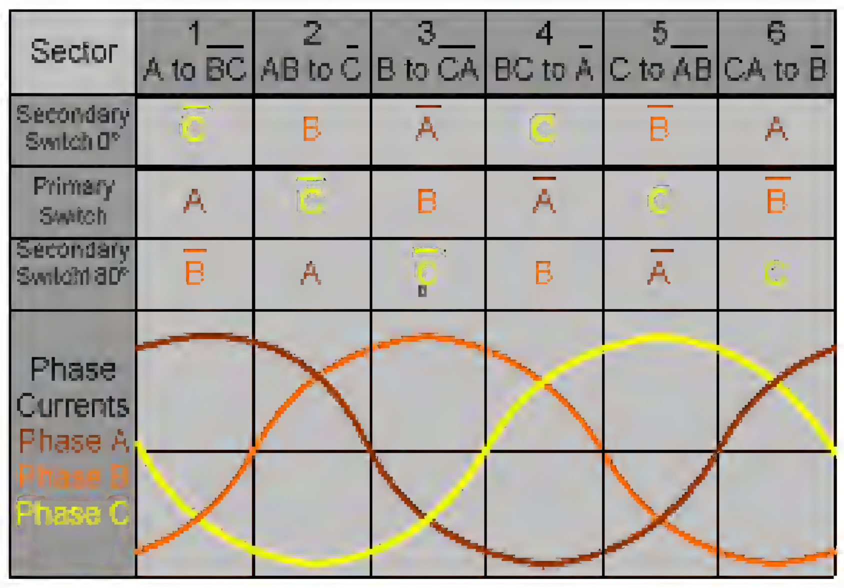

Figure 12: Switching Sector Definitions for CSR

Additionally for each sector the switching functions for the two secondary devices are phase shifted from each other by 180°. This is accomplished in the present controls hardware by shifting one of the triangle carriers of the actively switching PWM channels by 180°. Interleaving of switching functions results in an effective doubling of the switching frequency, which reduces the size and weight of the DC link inductor.

VSI Controls

For control of the motor, the VSI controls use a synchronous frame regulator typical of most commercial and industrial PM motor drives. A shaft velocity PID loop is cascaded into inner direct and quadrature (d-q) current PID loops. By default the velocity set point is received over the network interface from an upstream system controller or generated locally using the integrated HMI interface. Depending upon the application the VSI can also support an outer position, pressure, or temperature loop to generate a velocity set point through the use of sensor option cards.

MATLAB MODELING AND SIMULATION RESULTS

Here simulation is carried out in different cases 1). Open Loop Operation of Sine-Wave Input/output BLDC Inverter. 2). Closed Loop Operation of Sine-Wave Input/output BLDC Inverter.

Case 1: *Open Loop Operation of Sine-Wave Input/output BLDC Inverter.*

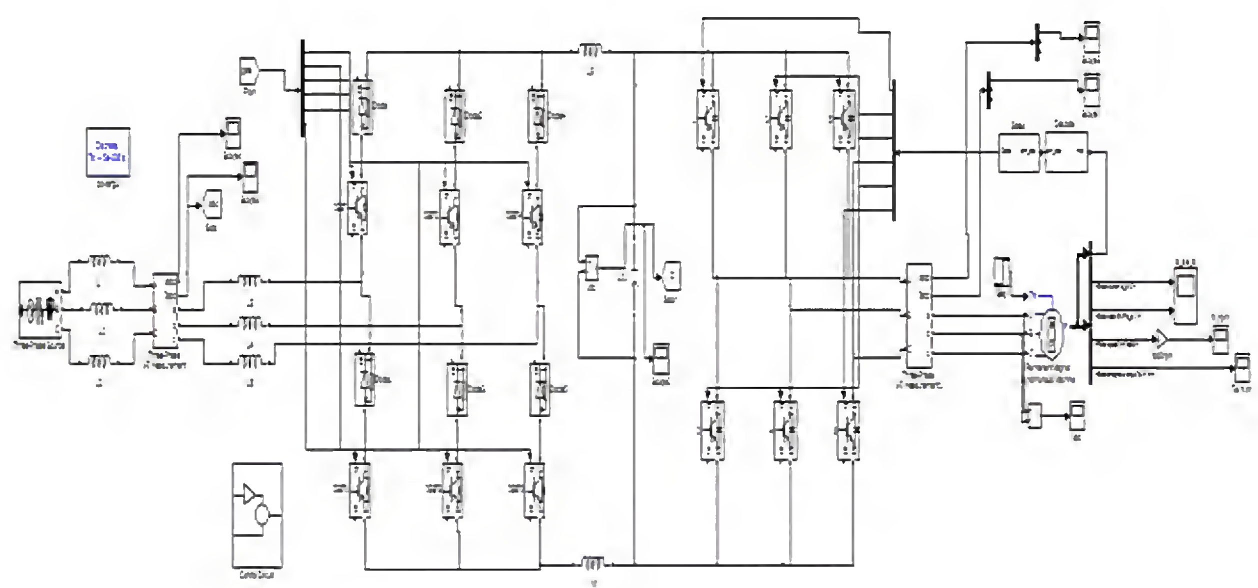

Figure 13: Matlab/Simulink Model of Proposed Open Loop Operation of Sine-Wave Input/Output BLDC Inverter

Figure 13 shows the Matlab/Simulink model of proposed Open Loop Operation of Sine-Wave Input/output BLDC Inverter.

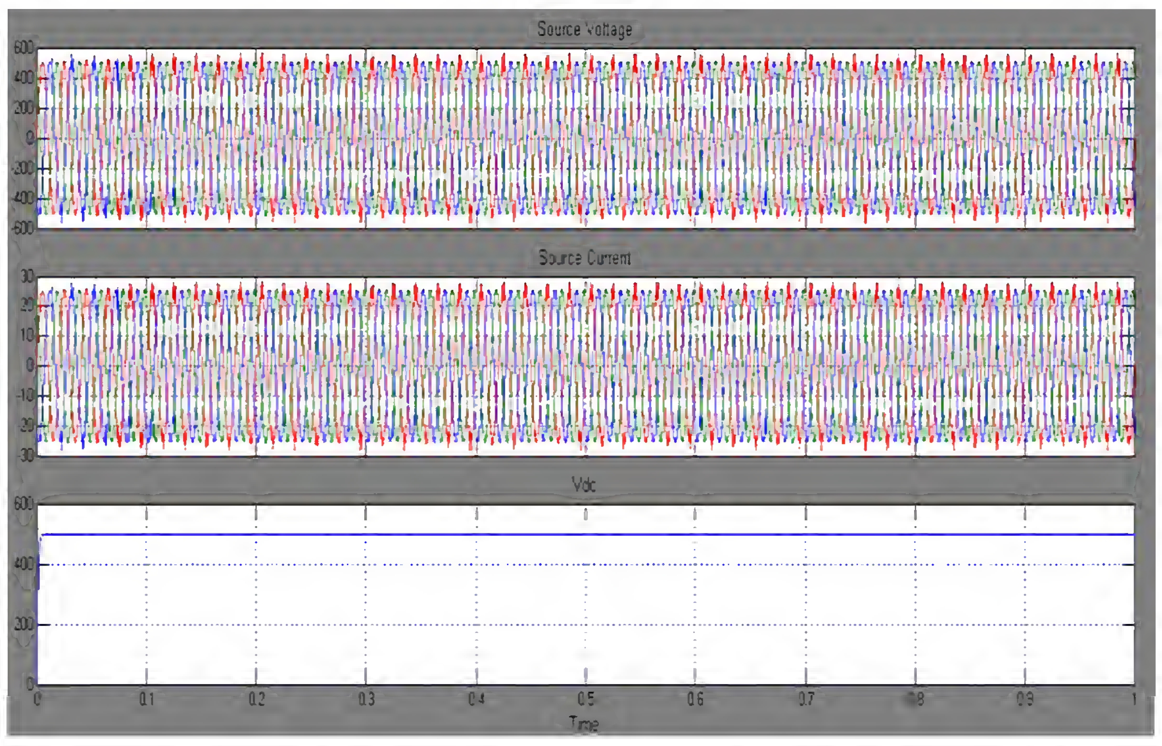

Figure 14: Source Voltage, Source Current, Vdc

Figure 14 shows the Source Voltage, Source Current, and Vdc of Open Loop Operation of Sine-Wave Input/output BLDC Inverter.

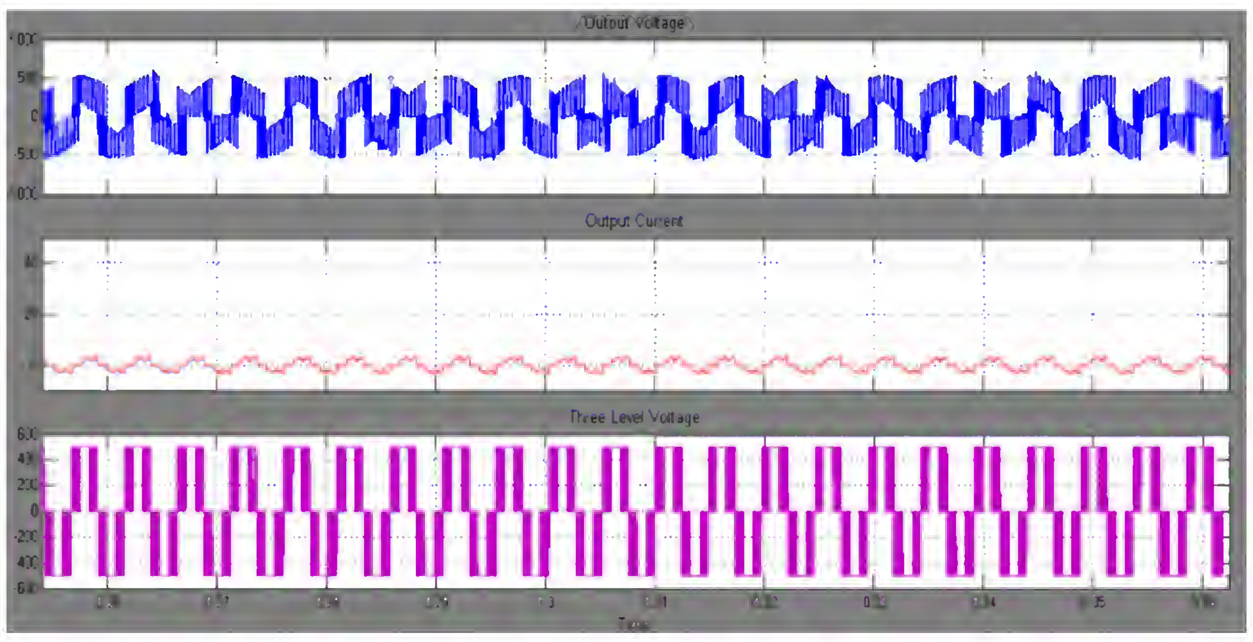

Figure 15: Output Voltage, Output Current, Three Level Voltages

Figure 15 shows the Output Voltage, Output Current, and Three Level Voltage of Open Loop Operation of Sine-Wave Input/output BLDC Inverter.

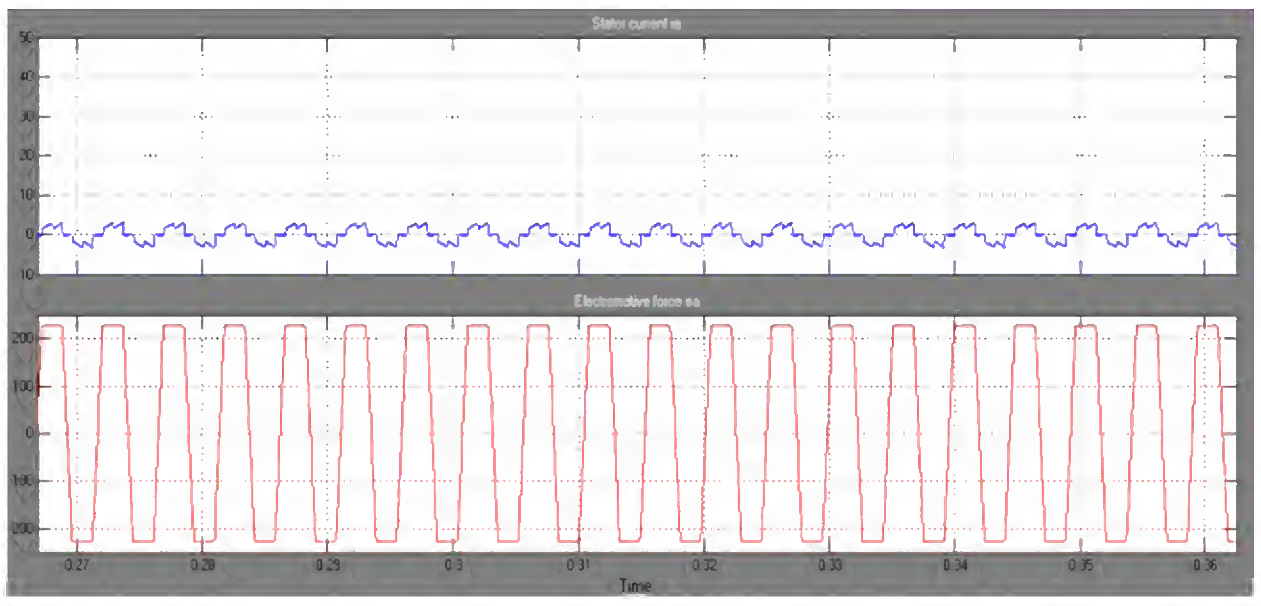

Figure 16: Stator Current & Back EMF

Figure 16 shows the Stator Current & Back EMF of Open Loop Operation of Sine-Wave Input/output BLDC Inverter.

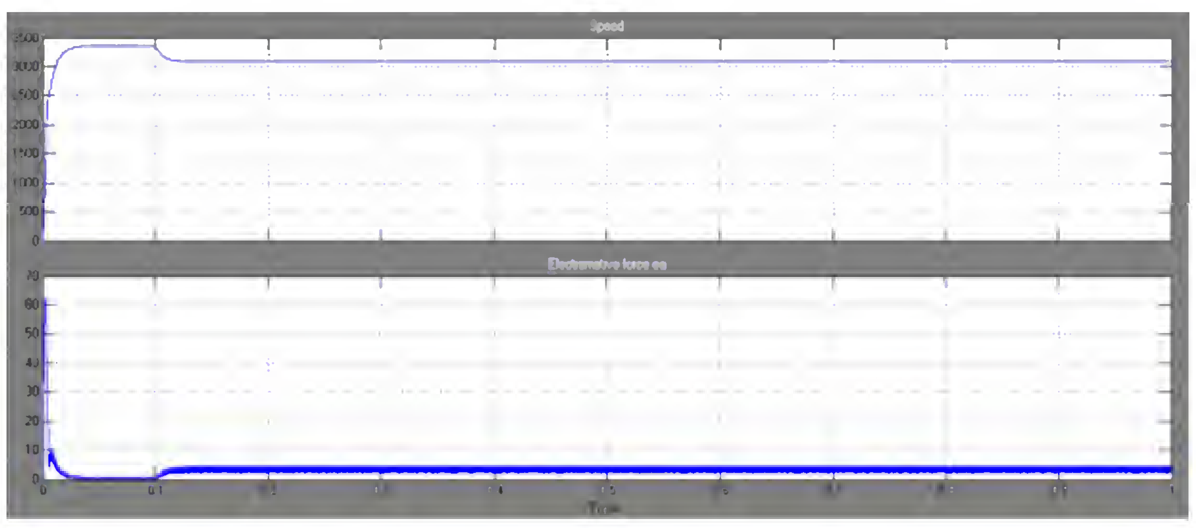

Figure 17: Speed & Electromagnetic Torque

Figure 17 shows the Speed & Electromagnetic Torque of Open Loop Operation of Sine-Wave Input/output BLDC Inverter.

Case 2: *Closed Loop Operation of Sine-Wave Input/output BLDC Inverter.*

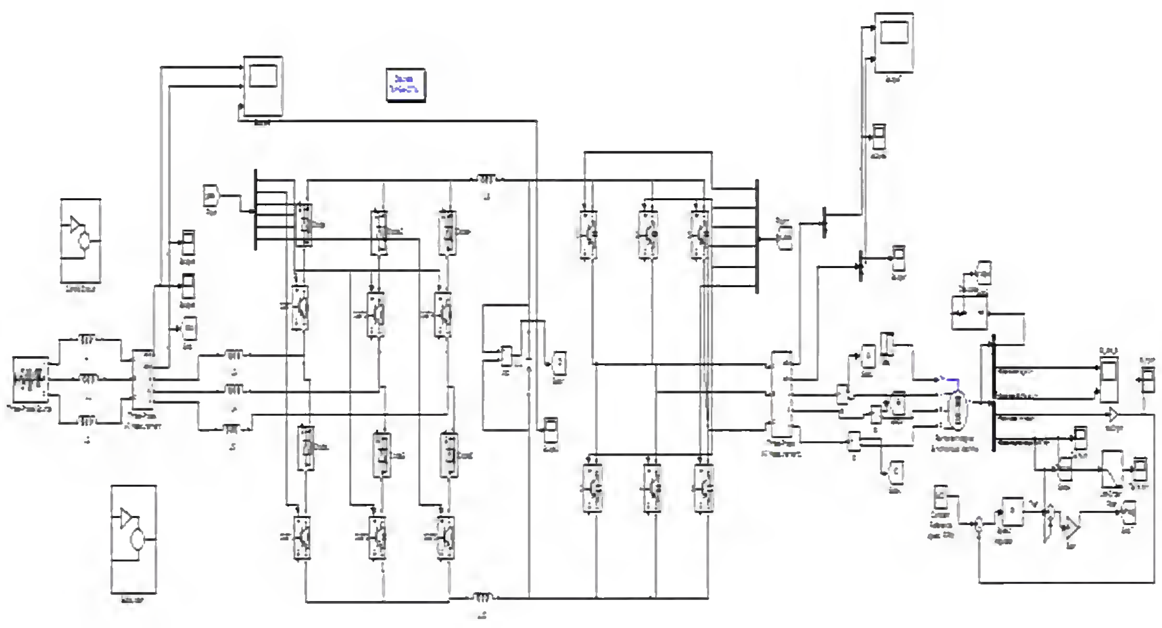

Figure 18: Matlab/Simulink Model of Proposed Closed Loop Operation of Sine-Wave Input/Output BLDC Inverter

Figure 18 shows the Matlab/Simulink model of proposed Closed Loop Operation of Sine-Wave Input/output BLDC Inverter.

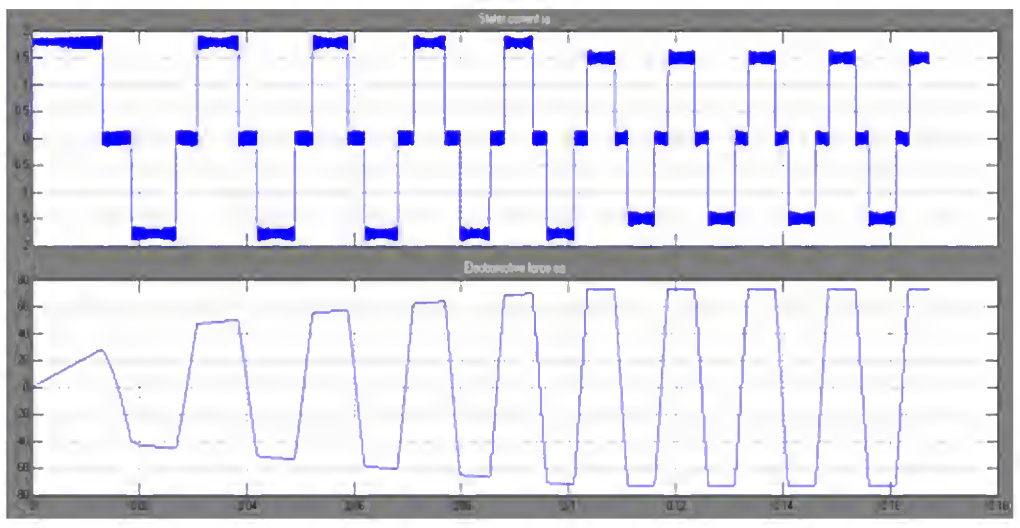

Figure 19: Stator Current, Back EMF

Figure 19 shows the Stator Current, Back EMF of Closed Loop Operation of Sine-Wave Input/output BLDC Inverter

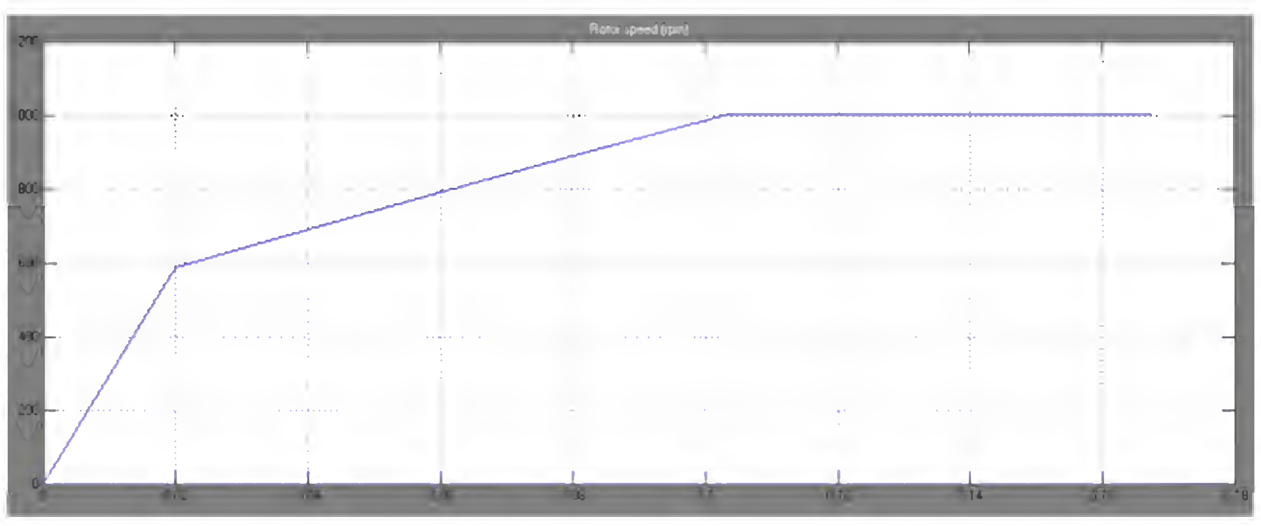

Figure 20: Speed

Figure 20 shows the Speed of Closed Loop Operation of Sine-Wave Input/output BLDC Inverter.

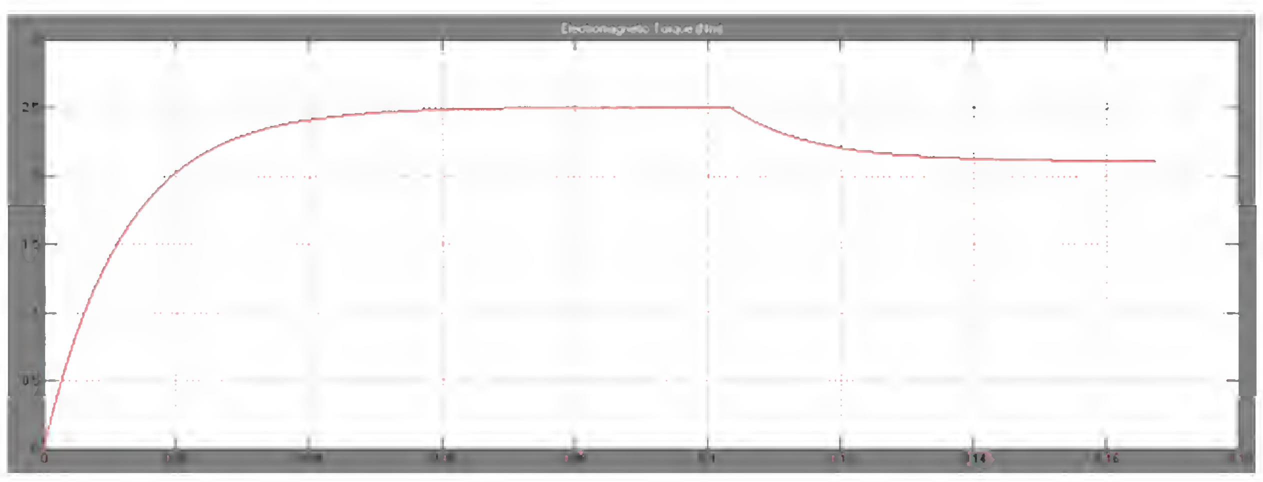

Figure 21: Electromagnetic Torque

Figure 21 shows the Electromagnetic Torque of Closed Loop Operation of Sine-Wave Input/output BLDC Inverter.

CONCLUSIONS

This paper has presented a open loop & closed loop topological configuration that combines an active buck rectifier or a PWM CSR with a buck inverter driving a PM motor, or a BLDC VSI in a cascaded configuration. The approach is demonstrated to have significant advantages in comparison to the classical Phase controlled CSR cascaded with a BLDC VSI, or a more modern PWM VSR cascaded with a BLDC VSI. A discussion of open loop & closed loop topological circuit elements, trade-offs related to parasitic features such as EMI, start-up/in-rush, etc have been discussed in the paper, illustrating the advantages of the proposed approach. A control approach for the overall system is presented to synthesize sinusoidal motor voltages, and sinusoidal input currents.

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